SPECIFICATION

RECONFIGURABLE LOGIC CIRCUIT USING A TRANSISTOR HAVING SPIN-DEPENDENT TRANSFER CHARACTERISTICS

FIELD OF THE INVENTION

The present invention relates to logic circuits with reconfigurable functions, and more particularly, to a reconfigurable logic circuit using transistors (hereafter referred to as the "spin transistors") that contain ferromagnetic bodies and have transfer characteristics depending on the magnetization states of the ferromagnetic bodies.

BACKGROUND OF THE INVENTION

Recently, attention has been drawn to logic circuits that can reconfigure (or reprogram) functions in accordance with user programs. For example, a field programmable logic array (FPGA) that has been developed by the LSI technique is widely used (disclosed by S. Trimberger in Proc. IEEE 81 (1993) pp. 1030-1041, S. Hauck in Proc. IEEE 86 (1998) pp. 615-638, and Toshinori Sueyoshi in "Programmable Logic Devices" IEICE Tech. Report, Vol.101, No.632, (2002) pp. 17-24, for example). Conventionally, the FPGA has been used only for test products and limited products. However, since shipment can be made quickly and the functions can be rewritten after shipment, the FPGA is incorporated as the last component into mobile devices such as portable telephone devices that tend to be replaced with newly developed devices in a short time. Also, studies have been made on the FPGA as an information device of novel architecture that reconfigures its hardware for each operation.

There are several types of configurations for the FPGA. Among them, the Look Up Table (LUT) method using SRAMs is most widely used. In this configuration,

small-sized logic blocks that are formed with LUTs for achieving desired functions are arranged in a matrix fashion, and the blocks are connected to one another with lines that can be changed by a switch (a pass transistor, for example) (see Fig. 57A).

A desired logic circuit is realized by rewriting the values to be written in the register of the LUT and the switch for the lines. Each logic block includes a flip-flop (FF) for operations in synchronization with the LUT (see Fig. 57B). The LUT includes a decoder circuit for matching each input pattern with an address, and memories (SRAM cells) for storing a value in the register of each address. Fig. 57C shows an example of the LUT circuit that can achieve symmetric Boolean functions.

A SRAM is a volatile memory, and loses stored information when the power supply is cut off. Therefore, so as to maintain data, a non-volatile memory (a flash memory, for example) is prepared externally, and the information stored in the non-volatile memory is loaded every time the power supply is resumed.

Recently, studies have been made on a circuit that has a neuron MOS (hereinafter referred to as the "νMOS") in the logic circuit blocks. This circuit has been developed as a reconfigurable logic circuit based on principles entirely different from those of the FPGA according to the LUT method (disclosed by T. Shibata and T. Ohmi in IEEE Trans. Electron Dev. ED-39 (1992) pp. 1444-1455 and IEEE Trans. Electron Dev. ED-40 (1993) pp. 570-576, and by Hiroshi Sawada, Kazuo Aoyama, Akira Nagoya, and Kazuo Nakajima in "Consideration for a Reconfigurable Logic Device using Neuron MOS Transistors", IEICE Tech. Report, Vol.99, No.481, (1999) pp. 41-48). Using νMOS, symmetric functions can be efficiently realized. Although the functions are limited compared with the functions according to

the LUT method, attention is being drawn to this method, as a large number of symmetric functions appear in the stage of logic design.

Fig. 56 illustrates an example structure of a logic circuit that can achieve symmetric Boolean functions. This logic circuit includes three pre-inverters 201, 203, and 205 that employ νMOS structures, and a main inverter 207 that also employs the νMOS structure. In the pre-inverters that serve as input units, digital values are input via equal capacitances. The inverters 201, 203, 205, and 207 have different logic threshold values from one another. In the drawing, V_k/n indicates that the number of inputs to the inverter is n, and the logic threshold value is V_k/n with respect to the logic level "1".

Also, inputs are denoted by A and B, and the input of each control signal is denoted by C_k (k = 0, 1, 2). The input to the main inverter 207 is controlled with C_k, thereby achieving a desired symmetric function. In the operation of this circuit, if C_k is "1", the output is "0" only when the number of "1"s in the input is k. In other cases, the output is "1". For example, if C_0 and C_2 are "1" and C_1 is "0", the output is "0" when the number of "1"s is 0 (A = B = "0") and when the number of "1"s is 2 (A = B = "1"), but the output is "1" when the number of "1"s is 1 (A or B = "1"). Thus, a XOR logic circuit is obtained.

DISCLOSURE OF THE INVENTION

The above described logic blocks of the FPGA have the following problems. More specifically, the logic blocks that utilizes the LUT method and νMOS have problems in the volatility of logic functions. Also, problems are caused with respect to the number of devices (the occupied area).

First, the problems with the logic blocks according to the LUT method are described. In

accordance with the LUT method, the circuit does not have capacity to rewrite to reconfigure logics, but refers to the values stored in the registers. SRAMs are employed for LUTs, the problems are caused by the volatility of the SRAMs. When the power supply is cut off, the contents of the LUTs, or the logic functions, are lost. In a case where the circuit is incorporated into a product, it is necessary to externally provide a non-volatile memory with an extremely large capacity for maintaining data. As a result, the area of the entire chip becomes larger, and the power consumption increases as a longer start-up time is required when power supply is resumed.

Also, in a case where a large number of devices (forty transistors are required in the circuit of Fig. 57C, for example) are employed to achieve symmetric Boolean functions with decoders and SRAM cells including transistors in the logic blocks, the area occupied by the logic blocks becomes larger.

Next, the problems with the logic blocks using νMOS are described. In such logic blocks, the operation of the circuit can be rewritten with a control signal, unlike in the logic blocks according to the LUT method. For two inputs, the number of MOSFETs is 8, and the number of capacitors is 14, which are almost half of the number of devices required according to the LUT method. However, the area occupied by the capacitors for the νMOS structure is not small. Also, to maintain the functions of the circuit, a control signals needs to be constantly supplied during the use of the circuit. It is also necessary to prepare a control signal of a size different from the supply voltage and to employ a control circuit (a controller) for controlling the control signal. Since functions cannot be stored in a non-volatile manner, there is a problem in the maintenance of the non-volatility for logic functions, as with the LUT method.

It is therefore an object of the present invention to provide a non-volatilely reconfigurable circuit with a small number of devices. Such a circuit should be small in size and have low power consumption.

In a circuit in accordance with the present invention, a transistor (hereinafter referred to as "spin transistor") with transfer characteristics that depend on the spin direction of the conduction carriers or the magnetization states of the ferromagnetic bodies in the transistor is employed, and the input of the transistor is formed with a νMOS transistor. The operating point of the circuit is adjusted to rewrite functions by varying the driving force of the transistor through the control of the magnetization state of the spin transistor. This circuit is based on a novel technique of rewriting functions entirely in terns of hardware, as the characteristics of the device are changed. This circuit differs from a logic block only with a νMOS in that logic functions can be maintained in a non-volatile manner and a control signal is not required for switching logic functions. Furthermore, the functions of the circuit can be stored in a non-volatile manner, by virtue of the ferromagnetic bodies in the spin transistor. Using such a logic circuit of the present invention, the above described problems in FPGA can be eliminated.

The non-volatility is now described. The functions of a circuit are determined by the magnetization states of the ferromagnetic bodies included in the spin transistor. Accordingly, even when the power supply is cut off, the logic functions are maintained in a non-volatile manner, as the magnetization states do not change. In view of this, the portion corresponding to a logic block unit that is necessary in the conventional FPGA becomes unnecessary in an external non-volatile memory. This is advantageous in reducing the chip size. Furthermore,

the time for loading logic functions is not required. Accordingly, the time required for start-up can also be shortened.

In a circuit in accordance with the present invention, the logic block includes nine to eleven MOSFETs and two capacitors. Accordingly, the number of devices decreases to a third of the number of device in the LUT structure or even less than that. Compared with a logic block using only a νMOS, the number of devices is halved. Since the external non-volatile memories are employed only for the line unit, the total number of devices is much smaller than that in a conventional circuit.

A spin transistor can be employed as a switch for selecting the line that connects logic blocks. Especially, a spin MOSFET that is described later is employed as the switch, so that the mutual lines between logic blocks can also be stored in a non-volatile manner. In such a case, a non-volatile memory becomes unnecessary for the line unit. The spin MOSFET as the switch may be a depletion MOSFET or an enhancement MOSFET. Further, a transfer gate that is formed with p-channel and n-channel spin MOSFETs can also be employed.

One aspect of the present invention can provide a circuit that includes a spin transistor having transfer characteristics depending on the spin direction of conduction carriers. In this circuit, the spin direction of the conduction carriers is changed so as to vary the transfer characteristics of the spin transistor, and an operating point is changed based on the transfer characteristics, thereby reconfiguring a function.

An A-D converter is connected to an output terminal of the circuit, so that the analog operating point at the output terminal is converted to a digital logic level. Also, the A-D converter includes a spin

transistor, so that functions can be reconfigured by setting a threshold value depending on the magnetization state of the spin transistor.

Instead of the spin transistor, another spin transistor with variable transfer characteristics can be employed in the circuit. In such a case, the operating point is also moved by changing the transfer characteristics of the transistor, thereby reconfiguring functions. Here, the "variable transfer characteristics" are variable solid-state properties other than the biases such as V_{ds} and V_{gs}, and the transfer characteristics of a transistor can be varied in a non-volatile manner. Accordingly, the output characteristics vary, even when biases are applied under the same conditions. Such a transistor can be realized with a ferromagnetic material or a ferroelectric material, or can be formed by a floating gate technique (by which carriers are injected to a floating gate so as to change a threshold value). The above described spin transistor is one of the transistors with variable transfer characteristics.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A and 1B are block diagrams each illustrating the fundamental structure of a circuit in accordance with the present invention;

Fig. 2A illustrates an example structure of a MOSFET-type spin transistor (hereinafter referred to as "spin MOSFET");

Fig. 2B illustrates an example structure of a νMOS (B);

Fig. 3A shows the idealized static characteristics of a spin MOSFET;

Fig. 3B shows the gate voltage dependence of the drain current;

Fig. 4 shows the static characteristics of the νMOS transistor of Fig. 2B, with the inputs A and B

being digital values;

Figs. 5A, 5B, and 5C show AND/OR reconfigurable logic circuits with E/E, E/D, and CMOS inverter structures;

Fig. 6 illustrates an example structure of a NAND/NOR reconfigurable logic circuit, with a CMOS inverter for an input;

Fig. 7 illustrates an AND/OR circuit with a n-channel spin MOSFET of a depletion type;

Fig. 8 shows the operating curve of an AND/OR circuit with the n-channel spin MOSFET of a depletion type;

Figs. 9A and 9B are truth tables of the AND/OR circuit with the n-channel spin MOSFET of a depletion type;

Fig. 10 illustrates a circuit that has a XNOR function added to the circuit illustrated in Fig. 7;

Fig. 11 illustrates a first operation of the circuit illustrated in Fig. 10;

Fig. 12A shows the operating curve of the AND/OR function;

Fig. 12B shows a truth table of the OR circuit;

Fig. 12C shows a truth table of the AND circuit;

Fig. 13A shows the operating curve of the XNOR function;

Fig. 13B shows a truth table of the XNOR circuit;

Fig. 14A illustrates a third operation of the circuit illustrated in Fig. 10;

Fig. 14 is a truth table of the operation;

Fig. 15 illustrates the structure of a circuit that can reconfigure all the symmetric Boolean functions;

Fig. 16A illustrates the circuit structure of a threshold value variable inverter;

Fig. 16B illustrates an example operation of the inverter;

Fig. 17 has the threshold value of a conventional

CMOS inverter as the function of the ratio of β of a pMOS to β of an nMOS;

Fig. 18 illustrates an example structure of an AND/OR circuit;

Fig. 19A shows a first operation of the circuit illustrated in Fig. 18;

Fig. 19B shows a truth table of the operation;

Fig. 20 shows a second operation of the circuit illustrated in Fig. 18;

Fig. 20B shows a truth table of the operation;

Fig. 21 shows another example structure of an AND/OR circuit;

Fig. 22A shows the characteristics of the variable threshold value inverter of Fig. 21;

Fig. 22B shows a truth table of the inverter;

Fig. 23A corresponds to Fig. 22A, showing the operation when the threshold value is varied;

Fig. 23B corresponds to Fig. 22B, showing truth table;

Fig. 24 illustrates an example structure of an AND/OR/XNOR circuit;

Fig. 25 shows the operating curve of Vin_n of the circuit illustrated in Fig. 24;

Fig. 26A shows a first operation of the circuit illustrated in Fig. 24;

Fig. 26B shows a truth table of the operation;

Fig. 27A shows a second operation of the circuit illustrated in Fig. 24;

Fig. 27B shows a truth table of the operation;

Fig. 28A shows a third operation of the circuit illustrated in Fig. 24;

Fig. 28B shows a truth table of the operation;

Fig. 29A shows a fourth operation of the circuit illustrated in Fig. 24;

Fig. 29B shows a truth table of the operation;

Fig. 30 illustrates an example structure of an AND/OR/XOR/XNOR circuit;

Fig. 31 shows the operating points of Vin_p of the circuit illustrated in Fig. 30;

Fig. 32A shows a first operation of the circuit illustrated in Fig. 30;

Fig. 32B shows a truth table of the operation;

Fig. 33A shows a second operation of the circuit illustrated in Fig. 30;

Fig. 33B shows a truth table of the operation;

Fig. 34A shows a third operation of the circuit illustrated in Fig. 30;

Fig. 34B shows a truth table of the operation;

Fig. 35A shows a fourth operation of the circuit illustrated in Fig. 30;

Fig. 35B shows a truth table of the operation;

Fig. 36 illustrates an example structure of a reconfigurable logic circuit with a spin MOSFET;

Fig. 37 illustrates an example structure of a NAND/NOR circuit;

Fig. 38 shows the operating points of the circuit illustrated in Fig. 37, and the characteristics of the inverter;

Fig. 39 shows a truth table of the circuit illustrated in Fig. 37;

Fig. 40 is a circuit diagram of a NAND/NOR/XNOR circuit;

Fig. 41 shows the operating points of Vin_n of the circuit illustrated in Fig. 40;

Fig. 42A shows a first operation of the circuit illustrated in Fig. 40;

Fig. 42B shows a truth table of the operation;

Fig. 43A shows a second operation of the circuit illustrated in Fig. 40;

Fig. 43B shows a truth table of the operation;

Fig. 44 is a circuit diagram of a NAND/NOR/XNOR/XOR circuit;

Fig. 45 shows the operating points of Vin_p of the circuit illustrated in Fig. 44;

Fig. 46A shows a first operation of the circuit illustrated in Fig. 44;

Fig. 46B shows a truth table of the operation;

Fig. 47A shows a second operation of the circuit illustrated in Fig. 44;

Fig. 47B shows a truth table of the operation;

Fig. 48 illustrates an example structure of a NAND/NOR circuit (E/E configuration);

Fig. 49 illustrates the operation of the circuit illustrated in Fig. 48;

Fig. 50 shows truth tables of the NOR circuit and the NAND circuit shown in Fig. 48;

Fig. 51A illustrates an example structure of an NAND/NOR/XNOR circuit;

Fig. 51B shows the operating points of Vin_n of the circuit illustrated in Fig. 51A;

Fig. 52A shows a first operation of the circuit illustrated in Fig. 51A;

Fig. 52B shows a truth table of the operation shown in Fig. 52A;

Fig. 53A shows a second operation of the circuit illustrated in Fig. 51A;

Fig. 53B shows a truth table of the operation shown in Fig. 53A;

Fig. 54A shows a third operation of the circuit illustrated in Fig. 51A;

Fig. 54B shows a truth table of the operation shown in Fig. 54A;

Fig. 55 illustrates the structure of a circuit that can reconfigure all the symmetric Boolean functions;

Fig. 56 illustrates an example structure of a logic circuit with which symmetric Boolean functions can be realized;

Fig. 57A shows a circuit in which small-sized logic blocks having LUTs and memory devices that can achieve desired functions are arranged in a matrix

fashion, and the blocks are connected with lines that can be changed by a switch (a pass transistor, for example);

Fig. 57B shows a circuit that includes a flip-flop (FF) for operating in synchronization with a LUT; and

Fig. 57C shows an example of a LUT circuit with which symmetric Boolean functions can be realized.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Figs. 1A and 1B, the fundamental structure of a circuit in accordance with the present invention is described. As shown in Figs. 1A and 1B, the circuit in accordance with the present invention includes a terminal V_m (hereinafter, "V_m" will be used as the name of the terminal, but will also be used as the potential of the terminal), a circuit group P that charges the terminal V_m with parasitic capacitance and the next stage with input capacitance, a circuit group Q for discharging, and an A-D converter that amplifies the analog voltage V_m to a digital logic level. The voltage V_m is determined by the values of input signals A and B, regardless of the circuit of the next stage.

As shown in Fig. 1A, a spin transistor is contained in at least one of the circuit groups P and Q, and the current control capacity can be controlled in accordance with the magnetization state of the spin transistor. Therefore, even if the input signals A and B have the same values, the voltage V_m varies depending on the magnetization state of the spin transistor. The variation of V_m caused by a change in the magnetization sate of the spin transistor is amplified to the digital logic level by the A-D converter having a predetermined logic threshold value, thereby forming a reconfigurable logic circuit. Alternatively, with an A-D converter that can change the logic threshold value using the spin transistor, a reconfigurable logic circuit can be

formed.

The circuit shown in Fig. 1B has a 2-input ν-MOS structure with equally weighted inputs. In a symmetric function, the input signals A and B do not need to be distinguished from each other. Accordingly, with the 2-input ν-MOS structure having equally weighted inputs, inputs can be efficiently performed to the circuit groups. If there is a need to distinguish the input signals A and B from each other, the weights on the input capacity should be made different from each other between the input signals A and B.

The circuit in accordance with the present invention contains ferromagnetic bodies made of a ferromagnetic metal or the like. This circuit is a non-volatile, reconfigurable circuit, and more particularly, is a logic circuit that employs a spin transistor that can control its transfer characteristics in accordance with the spin direction of the conduction carriers or the magnetization states of the ferromagnetic bodies. Using the spin transistor, a symmetric Boolean function can be realized with a small number of components.

In the following, the spin transistor is described in greater detail. The spin transistor has at least one ferromagnetic body (free layer) with a magnetization direction that can be independently controlled with a magnetic field or the like, and at least one ferromagnetic body (pin layer) with a fixed magnetization direction. In this spin transistor, the relative magnetization state between the free layer and the pin layer can be switched between parallel magnetization and antiparallel magnetization by changing the magnetization direction of the free layer.

In the spin transistor, output characteristics in accordance with the magnetization state inside can be realized by virtue of the conduction phenomena, such as spin-dependent scattering, a spin-dependent tunneling

effect, and a spin filter effect, which depend on the spin direction of the carriers and the magnetization directions of the ferromagnetic bodies. Accordingly, the transfer characteristics of the spin transistor can be controlled in accordance with the relative magnetization direction of the pin layer with respect to the free layer contained in the spin transistor, even when the same biases are applied.

In the following, an example case where the spin transistor is a MOSFET spin transistor (hereinafter referred to as "spin MOSFET") is described. Although spin-dependent conduction phenomena are included, the transistor operation is based on the same principles as those of the operation of a conventional MOSFET. Particularly, the output characteristics can be represented by gradual channel approximation.

Fig. 2A illustrates an example structure of a spin MOSFET. As shown in Fig. 2A, the spin MOSFET (A) is formed on a semiconductor (substrate) 1, and has the same structure as a conventional MOSFET, including the aspect that a gate electrode 7 is formed on a gate insulating film 11. The spin MOSFET (A) differs from a conventional MOSFET in that a source electrode 3 and a drain electrode 5 are made of a ferromagnetic material. Hereinafter, the source electrode made of a ferromagnetic material will be referred to simply as the ferromagnetic source 3, and the drain electrode made of a ferromagnetic material will be referred to simply as the ferromagnetic drain 5. In the drawings, "FM" indicates "ferromagnetic metal", but the source and drain may be made of some other electric conductive ferromagnetic material.

The ferromagnetic source 3 serves as a spin injector that injects spin-polarized carriers to a channel formed below the gate in the semiconductor 1. The ferromagnetic drain 5 serves as a spin analyzer that detects an electric signal representing the

direction of the spins injected to the channel. In a case where a ferromagnetic metal (FM) is employed as the ferromagnetic material, the ferromagnetic source 3 and the ferromagnetic drain 5 are formed with the Schottky junctions with the semiconductor (substrate) 1. A gate voltage is applied to the gate electrode 7, so that spin-polarized carriers can be injected from the ferromagnetic source 3 to the channel via a Schottky barrier.

The injected spin-polarized carriers reach the ferromagnetic drain 5 via the channel (for ease of explanation, the Rashba effect caused by the gate field of the spin-polarized carriers injected to the channel is ignored). In a case where parallel magnetization is observed between the source and the drain, the spin-polarized carriers injected to the ferromagnetic drain 5 become a drain current, without adverse influence of spin-dependent scattering. In a case where antiparallel magnetization is observed, on the other hand, the ferromagnetic drain 5 is subjected to the resistance due to spin-dependent scattering. Accordingly, in the spin MOSFET, the current drive force varies depending on the relative magnetization direction between the source and the drain.

Figs. 3A and 3B show idealized static characteristics of a spin MOSFET. With a gate voltage equal to or lower than a threshold value ($V_{gs} < V_{th}$), the spin MOSFET is in an OFF state, as in the case of a conventional MOS transistor. This does not change with the magnetization state of the spin MOSFET. When a gate voltage equal to or higher than the threshold value ($V_{gs} = V_{gs1} < V_{th}$) is applied, the spin MOSFET is put into an ON state. However, even when the same gate voltage is applied, the drain current I_d varies depending on the magnetization state of the ferromagnetic bodies included in the spin MOSFET. In the case of parallel magnetization, a high drain

current $I_{d\uparrow\uparrow}$ flows. In the case of antiparallel magnetization, a low drain current $I_{d\uparrow\downarrow}$ flows. If the drain current of the spin MOSFET can be represented using the same gain coefficient as that of a conventional MOSFET, the gain coefficient is high in the case of parallel magnetization, and the gain coefficient is low in the case of antiparallel magnetization. In the following, relative parameters β representing the gain coefficients of the spin MOSFETs and the MOSFETs are introduced. With the gain coefficients of the spin MOSFETs and the MOSFETs included in the circuit being β_{G1}, β_{G2} ... β_{GN} (for the spin MOSFET, the gain coefficient in the case of parallel magnetization is set separately from the gain coefficient in the case of antiparallel magnetization), the gain coefficient of the spin MOSFETs and the MOSFETs can be expressed as $\beta_{G1}=\beta_1\beta_{G1}$, $\beta_{G2}=\beta_2\beta_{G1}$, $\beta_{G3}=\beta_3\beta_{G1}$ ... $\beta_{GN}=\beta_N\beta_{G1}$, using the gain coefficient β_{G1}. With the coefficients $\beta_1(=1)$, β_2, ... β_N, the magnitude correlation among the gain coefficients of the transistors can be expressed. Although the magnitude correlation among the gain coefficients β_1, β_2, ... β_N is expressed with given numerals, the numeric values β are merely examples of representations of the magnitude correlation, and those numeric values do not limit the scope of the present invention. Also, the magnitude correlation among the gain coefficients β_1, β_2, ... β_N indicates an example of the magnitude correlation among output currents when the same bias is applied to the MOSFET and the spin MOSFET, including a case where the output characteristics of the spin MOSFET cannot be expressed with the output characteristics of the conventional MOSFET.

Next, a νMOS structure is described in conjunction with Fig. 2B and Fig. 4. As shown in Fig. 2B, a MOSFET (B) with a νMOS structure includes a

source 13 and a drain 15 that are formed on a semiconductor 11, a floating gate 21 formed above the semiconductor 11 via a gate insulating film 20, and two divided gate electrodes 17a and 17b. As described above, inputs A and B are input to the gates 17a and 17b of the νMOS structure via the input capacitances of the gate electrode and the floating gate. The inputs can be weighted by varying the magnitudes of the gate electrode and the floating gate. Here, a case where all the input capacitances are equal to one another is described as an example.

In the 2-input νMOS structure shown in Fig. 2B, the potential V_{fg} of the floating gate 21 is represented by the input mean value, which is V_{fg} = (A+B)/2, obtained by coupling of capacitances in a case where the gate capacitance can be ignored. Likewise, in a case of multiple inputs (n inputs (n>2)), it is safe to assume that the mean value of the n inputs is input to the floating gate. Fig. 4 shows the static characteristics in a case where the inputs A and B are digital values. However, the inputs may be analog values. As shown in Fig. 4, in the case of A = B = "0", the drain current I_d hardly flows. In the case of A = B = "1", the drain current I_d flows. When either A or B is "1", the drain current that is equivalent to that obtained by applying a gate voltage half the above described gate voltage is generated. In the symmetric function, the input signals A and B do not need to be distinguished from each other. Accordingly, using the equally-weighted 2-input νMOS structure, input can be efficiently performed to the circuit groups.

An AND/OR reconfigurable logic circuit can be realized using the inputs of the νMOS structure and an inverter structure having an E/E configuration, an E/D configuration, or a CMOS configuration formed with spin MOSFETS and conventional MOSFETS as the circuit structure of the circuit group P and the circuit group

Q. Figs. 5A, 5B, and 5C illustrate AND/OR reconfigurable logic circuits using the inverter structures of the E/E configuration, the E/D configuration, and the CMOS configuration. Hereinafter, each spin MOSFET will be indicated by a transistor symbol with an arrow. In the drawings, spin MOSFETs are used for active loads (Q2) of the inverters of the E/E configuration, the E/D configuration, and the CMOS configuration. However, spin MOSFETs may be used for drivers (Q1). Alternatively, both the active loads (Q2) and the drivers (Q1) may be formed with spin MOSFETs. The input νMOS structure is used for the drivers (Q1) in the E/E configuration and the E/D configuration. In the CMOS configuration, the νMOS structure is realized with a floating gate shared between Q2 and Q1. The inverter in the output stage is used to divide the output of V_m into the logic levels of "1" and "0". This inverter serves as an A-D converter. The active load Q2 in each of Figs. 5A through 5C forms the circuit group P, while the driver Q1 forms the circuit group Q. Further, an extra circuit for controlling the potential of V_m in each of the circuits of Figs. 5A through 5C is added to the circuit group P and the circuit group Q, thereby achieving a complicated, reconfigurable logic circuit.

As shown in Fig. 6, it is also possible to achieve the operation equivalent to that of the νMOS structure by employing CMOS inverters for inputs, instead of the capacitance coupling. In such a case, however, a logic function that is obtained by inverting the logic function of Figs. 5A through 5C is output.

Next, a reconfigurable logic circuit in accordance with a first embodiment of the present invention is described in conjunction with the accompanying drawings. In the logic circuit in accordance with this embodiment, the driver or the active load of an E/D inverter circuit formed with an

enhancement MOSFET and a depletion MOSFET is replaced with a spin MOSFET. To replace the driver, an enhancement spin MOSFET should be employed. To replace the active load, a depletion spin MOSFET should be employed. The input νMOS structure is used for the driver. As for the inverter of the output stage, a CMOS inverter is most preferred in terms of performance, but it is possible to employ an inverter of another type, such as an E/D inverter.

The load curve in the E/E configuration varies according to the voltage generated in the driver. With the E/D configuration, on the other hand, the load curve with the active load is saturated. Accordingly, a wider logic margin can be allowed.

1) AND/OR Circuit

Referring now to Figs. 7 through 9, an AND/OR circuit with a n-channel spin MOSFET of a depletion type is described. In Fig. 7, the n-channel spin MOSFET of a depletion type is denoted by Tr1, and the parameter β_{n1} can be 1 or 10 in the case of antiparallel magnetization or parallel magnetization. Since the source and the gate of Tr1 are short-circuited, the load curve is saturated with respect to Vm as indicated by the solid line in Fig. 8. A νMOS structure is used for the input of a transistor Tr2, and its operation can be as indicated by the broken line in Fig. 8. Figs. 9A and 9B are the truth tables of this circuit. Also, the details of the operation are shown in Table 1.

[Table 1]

β_{n1}	V_m A / B	0 / 0	0 / 1	1 / 1	V_{out} (in order of Vm)	function
1		V_O("1")	V_P("0")	V_Q("0")	"0" "1" "1"	OR
10		V_O("1")	V_R("1")	V_S("0")	"0" "0" "1"	AND

In a case where the circuit functions as an OR circuit, the spin MOSFET is put into the antiparalell magnetization configuration, and the parameter β_{n1} is set at 1, with which the current driving capacity is small. Here, in the case of A = B = "0", the operating point V_m is V_0 according to Fig. 8, and the output V_{out} is inverted and amplified to "0". In the case of A or B = "1" (hereinafter, (A, B) = ("1", "0") or (A, B) = ("0", "1") will be expressed simply as A or B = "1"), the operating point V_m is V_P, and accordingly, the output V_{out} is "1". In the case of A = B = "1", the operating point V_m is V_Q, and accordingly, the output V_{out} is "1".

In a case where the circuit functions as an AND circuit, the spin MOSFET is put into the paralell magnetization configuration, and the parameter β_{n1} is set at 10, with which the current driving capacity is large. Here, in the case of A = B = "0", the operating point V_m is V_0, and accordingly, the output V_{out} is "0". In the case of A or B = "1", the operating point V_m is V_R, and accordingly, the output V_{out} is "0". In the case of A = B = "1", the operating point V_m is V_S, and accordingly, the output V_{out} is "1".

2) AND/OR/XNOR Circuit

Fig. 10 illustrates a circuit in which an XNOR function is added to the circuit shown in Fig. 7. The XNOR function is added as a Q group that is a circuit in which the input/output correlation is the same as that in an AND circuit, in the case of A or B = "0" and A = B = "1", and V_{out} is "1" (V_m is "0") in the case of A = B = "0". In Fig. 10, the transistors Tr3 through Tr5 are the added part. The transistors Tr3 and Tr4 that forms an inverter serve as a level shifter. As shown in Fig. 11, the transistor Tr5 is energized (is put into an ON state) only when A and B are "0". The transistor Tr5 is a spin MOSFET, but the variation of

β_{n5} according to the magnetization state is designed to be greater than the variation of β_{n1} of the transistor 1. For example, β_{n5} is 0.5 or 50 in the case of antiparallel magnetization or parallel magnetization. In the case of parallel magnetization, β_{n5} is 50, with which a sufficiently high current (I_{d_high}) flows. In the case of antiparallel magnetization, β_{n5} is 0.5, with which the current value (I_{d_low}) is very small. Figs. 12A through 14B show the operating point V_m with respect to each parameter β. The sum of currents flowing through the transistors Tr2 and Tr5 is indicated by solid lines, and the current I_{d_low} can be ignored. The circuit functional correlation between β_{n1} and β_{n5} is shown in Table 2.

[Table 2]

β_{n1}	β_{n5}	V_m A B	0 0	0 1	1 1	V_{out} (in order of Vm)			function
1	0.5		V_O("1")	V_P("0")	V_Q("0")	"0"	"1"	"1"	OR
10	0.5		V_O("1")	V_R("1")	V_S("0")	"0"	"0"	"1"	AND
1	50		V_T("0")	V_R("1")	V_S("0")	"1"	"0"	"1"	XNOR
10	50		V_U("0")	V_R("0")	V_V("0")	"1"	"1"	"1"	all"1"

Referring first to Figs. 12A through 12C, the AND/OR function is described. The transistor Tr5 is put into an antiparalell magnetization configuration, and the current driving capacity is made very small (β_{n5} = 0.5). By doing so, the flowing current I_{d_low} can be ignored, and the corresponding portion is regarded as open. As a result, the circuit has the same structure as that of the circuit shown in Fig. 7, and the AND(Fig. 12C)/OR(Fig. 12B) function can be maintained.

Next, the XNOR function is described in conjunction with Figs. 13A and 13B. The transistor Tr5

is put into a paralell magnetization configuration, and the current driving capacity is made high (β_{n5} = 50). The transistor Tr2 is also put into a paralell magnetization configuration (β_{n1} = 10) as in the case of AND. In the case of A = B = "1" or A or B = "1", the transistor Tr5 is regarded as open, and accordingly, functions as an AND circuit. In the case of A = B = "0", V_m is discharged by the current I_{d_high} of the transistor Tr5, to obtain $V_m = V_T < V_{inv}$ and V_{out} = "1". Further, when the transistor Tr1 is put into an antiparalell magnetization configuration (β_{n1} = 1) and the transistor Tr5 is put into a paralell magnetization configuration (β_{n5} = 50), V_{out} becomes "1" for all the inputs (see Figs. 14A and 14B). This circuit is characterized in that the operating point V_m is always close to 0V or V_{dd}, and the logic margin is wide.

3) AND/OR/XNOR/NAND/NOR/XOR Functions

In a circuit shown in Fig. 15, another stage of an inverter circuit is added to the output. The details of the operation of this circuit are shown in Table 3. Basically, this circuit is the same as the circuit illustrated in Fig. 10, but all the symmetric Boolean functions can be realized with V_{out} and its inverted output.

[Table 3]

β_{n1}	β_{n5}	V_{out} A / B				$\overline{V_{out}}$ A / B				function
		A	0	0	1	A	0	0	1	
		B	0	1	1	B	0	1	1	
1	0.5		"0"	"1"	"1"		"1"	"0"	"0"	OR/NOR
10	0.5		"0"	"0"	"1"		"1"	"1"	"0"	AND/NAND
1	50		"1"	"0"	"1"		"0"	"1"	"0"	XNOR/XOR
10	50		"1"	"1"	"1"		"0"	"0"	"0"	all"1"/all"0"

Next, a reconfigurable logic circuit in accordance with a second embodiment of the present

invention is described in conjunction with the accompanying drawings. A logic circuit in accordance with this embodiment can be formed by using a spin MOSFET for either the n-channel MOSFET or the p-channel MOSFET in a CMOS inverter, or using spin MOSFETs for both the n-channel MOSFET and the p-channel MOSFET. The νMOS structure used for the input is formed with a floating gate shared by the n-channel device and the p-channel device. The inverter of the output stage is a conventional inverter of the CMOS configuration.

In accordance with this embodiment, the operating curve is saturated as in the E/D configuration, and accordingly, the mean logic margin can be made wider. Also, it is effective for low power consumption.

1) Threshold Value Variable Inverter

Fig. 16A is a circuit diagram of an inverter having a variable logic threshold value. In this circuit, the n-channel MOSFET and the p-channel MOSFET of a conventional CMOS inverter are replaced with a p-channel spin MOSFET. Here, the current driving capacity of the p-channel spin MOSFET in the case of parallel magnetization and antiparallel magnetization is made p_{inv} = 1 or 10, and the current driving capacity of the n-channel spin MOSFET is a value between 1 and 10. The logic threshold value of the inverter circuit shown in Fig. 16A varies according to the combination of parameters β. Fig. 16B shows the characteristics of both spin MOSFETs in a case where the parameter β_{ninv} is fixed while the parameter β_{pinv} is set to 1 or 10. Although the input is constant, the output V_{out} is V_L of the low level when the parameter β_{pinv} is 1, and the output V_{out} is V_H of the high level when the parameter β_{pinv} is 10. In this manner, the output V_{out} varies according to the current driving capacity of the p-channel spin MOSFET. More quantitatively, this can be explained as follows.

The inverter circuit shown in Fig. 16A can be

considered as the same as a conventional CMOS inverter. In such a case, the p-channel spin MOSFET and the n-channel spin MOSFET operate in the saturation region. With the drain current I_d flowing through the n-channel spin MOSFET and the p-channel spin MOSFET, the following equation can be obtained:

[Equation 1]

$$V_{inv} = \frac{V_{dd} - |V_{thp}| + V_{thn}\sqrt{\beta_{inv}}}{1 + \sqrt{\beta_{inv}}}$$

where

$$\beta_{inv} = \frac{\beta_{ninv}}{\beta_{pinv}}$$

Here, the logic threshold value V_{inv} is plotted as the function of the driving force ratio $\beta_{inv} = \beta_{ninv}/\beta_{pinv}$ in Fig. 17, with V_{dd} being 3.3V and V_{thn} being $|V_{thp}| = 0.5V$. As shown in Fig. 17, the threshold value according to the ratio $\beta_{inv} = 0.1, 1, 10$ can be obtained.

2) AND/OR

Fig. 18 illustrates an AND/OR circuit that employs the threshold value variable inverter shown in Fig. 16A. As shown in Fig. 18, the AND/OR circuit is formed with inverters of two stages. The inverter at the input side is a threshold value variable inverter, and the inverter at the output side is a conventional inverter (with a threshold value $V_{inv2} = V_{dd}/2$). The operating characteristics of the circuit shown in Fig. 18 are shown in Figs. 19A and 19B. In Fig. 19A, the solid line indicates the characteristics of the transistor Tr1, and the broken line indicates the characteristics of the transistor Tr2. The details of the operation of this circuit are shown in Table 4.

[Table 4]

β_{n1}	β_{n2}	V_m A 0 0 1 B 0 1 1	V_{out} (in order of Vm)	function
1	10	V_O("1") V_P("0") V_Q("0")	"0" "1" "1"	OR
10	1	V_O("1") V_R("1") V_Q("0")	"0" "0" "1"	AND

2-1) OR

Referring now to Figs. 19A and 19B, an OR circuit is described. In a case where the circuit illustrated in Fig. 18 functions as an OR circuit, the transistor Tr1 is put into an antiparalell magnetization configuration (β_{p1} = 1), and the transistor Tr2 is put into a paralell magnetization configuration (β_{n2} = 10). Here, in the case of A = B = "0", the operating point V_m is V_0 according to Fig. 19A, and the output V_{out} is inverted and amplified to "0". In the case of A or B = "1", the operating point V_m is V_P, and the output V_{out} is "1". In the case of A = B = "1", the operating point V_m is V_Q, and the output V_{out} is "1".

2-2) AND

Referring now to Figs. 20A and 20B, an AND circuit is described. The transistor Tr1 is put into a paralell magnetization configuration (β_{p1} = 10), and the transistor Tr2 is put into an antiparalell magnetization configuration (β_{n2} = 1). Here, in the case of A = B = "0", the operating point V_m is V_0, and the output V_{out} is inverted and amplified to "0". In the case of A or B = "1", the operating point V_m is V_R, and the output V_{out} is "0". In the case of A = B = "1", the operating point V_m is V_Q, and the output V_{out} is "1".

As can be seen from Figs. 21 through 23B, the threshold value V_{inv1} of the threshold value variable inverter (formed with the transistors Tr1 and Tr2) at the input side may be regarded as the reference value. In the following, the operation in such a case is described.

2-3) OR

When the transistor Tr1 is put into an antiparalell magnetization configuration (β_{p1} = 1) and the transistor Tr2 is put into a paralell magnetization configuration (β_{n2} = 10) in a circuit illustrated in Fig. 21, the logic threshold value V_{inv1} becomes V_{inv1_low} < $V_{dd}/2$, as shown in Fig. 22A. Also as shown in Figs. 22A and 22B, in the case of A = B = "0", V_{fg} becomes "0". Accordingly, the operating point V_m is V_0 = "1", and the output V_{out} is "0". In the case of A or B = "1", V_{fg} is $V_{dd}/2$ > V_{inv1_low}. Accordingly, the operating point V_m is V_P = "0", and the output V_{out} is "1". In the case of A = B = "1", V_{fg} is V_{dd}. Accordingly, the operating point V_m is V_Q = "0", and the output V_{out} is "1".

2-4) AND

When the transistor Tr1 is put into a paralell magnetization configuration (β_{p1} = 10) and the transistor Tr2 is put into an antiparalell magnetization configuration (β_{n2} = 1) in the circuit illustrated in Fig. 21, the logic threshold value V_{inv1} becomes V_{inv1_high} > $V_{dd}/2$, as shown in Fig. 23A. In the case of A = B = "0", V_{fg} becomes "0". Accordingly, the operating point V_m is V_0 = "1", and the output V_{out} is "0". In the case of A or B = "1", V_{fg} is $V_{dd}/2$ < V_{inv1_low}. Accordingly, the operating point V_m is V_R = "1", and the output V_{out} is "0". In the case of A = B = "1", V_{fg} is V_{dd}. Accordingly, the operating point V_m is V_Q = "0", and the output V_{out} is "1".

3) AND/OR/XNOR

Fig. 24 illustrates an AND/OR/XNOR circuit. The principles of the operation are the same as in the case of the circuit shown in Fig. 10. In the XNOR circuit, the input/output correlation is the same as that in the AND circuit in the case where A = B = "1" or A or B = "1", but is different from that in the AND circuit only in the case where A = B = "0", with V_{out} being "1" (V_m = "0"). This function can be realized by adding a circuit formed with the transistors Tr3, Tr4, and Tr5

(an n-channel spin MOSFET) to the circuit group Q. The inverter (a level shifter) formed with the transistors Tr3 and Tr4 has a threshold value V_{inv3} lower than $V_{dd}/2$. Accordingly, only in the case where A = B = "0", V_{in_n} becomes "1", and the transistor Tr5 is turned on. The variation in the current driving capacity β_{n5} of the transistor Tr5 between parallel magnetization and antiparallel magnetization is wider than that in the case of the transistors Tr1 and Tr2, and β_{n5} is 0.5 (antiparallel magnetization) or 50 (parallel magnetization). In the case of parallel magnetization (β_{n5} = 50), a sufficiently high current (I_{d_high}) flows, but in the case of antiparallel magnetization (β_{n5} = 0.5), the value of the current (I_{d_low}) is very small (see the upper and lower graphs in Fig. 25).

The details of the operation are shown in Table 5.

[Table 5]

β_{p1}	β_{n2}	β_{n5}	V_m A 0 0 1 B 0 1 1	V_{out} (in order of Vm)	function
1	10	0.5	V_O("1") V_P("0") V_Q("0")	"0" "1" "1"	OR
10	1	0.5	V_O("1") V_R("1") V_Q("0")	"0" "0" "1"	AND
1	10	50	V_T("0") V_P("0") V_Q("0")	"1" "1" "1"	all"1"
10	1	50	V_S("0") V_R("1") V_Q("0")	"1" "0" "1"	XNOR

3-1) AND/OR (see Figs. 26A and 26B, 27A and 27B)

As the transistor Tr5 is put into an antiparalell magnetization configuration (β_{n5} = 0.5), the current I_{d_low} can be ignored, and the transistor Tr5 can be regarded as open. Accordingly, the circuit becomes equivalent to the AND/OR circuit shown in Fig. 18.

3-2) XNOR (see Figs. 29A and 29B)

The transistor Tr5 is put into a paralell magnetization configuration (β_{n5} = 50). In the inverter part, the transistor Tr1 is put into a

paralell magnetization configuration (β_{p1} = 10), and the transistor Tr2 is put into an antiparalell magnetization configuration (β_{n2} = 1), as in the AND circuit. In the case where A = B = "1" or A or B = "1", the transistor Tr5 is equivalent to an open circuit, and operates in the same manner as the AND circuit. In the case where A = B = "0", V_m is discharged by the current I_{d_high} of the transistor Tr5, so as to be $V_m = V_S < V_{inv2}$. Accordingly, V_{out} becomes "1". Where the transistor Tr1 is put into an antiparalell magnetization configuration (β_{p1} = 1), the transistor Tr2 is put into a paralell magnetization configuration (β_{n2} = 10), and the transistor Tr5 is put into a paralell magnetization configuration (β_{n5} = 50), the output V_{out} becomes "1" for all the input patterns (see Figs. 28A and 28B).

Although all symmetric Boolean functions can be realized by adding an inverter to the output of the circuit shown in Fig. 24, a technique of achieving all the symmetric Boolean functions by adding a new circuit to the circuit group P is described below.

4) AND/OR/XNOR/XOR

Fig. 30 illustrates an AND/OR/XNOR/XOR circuit. In the XOR circuit, the input/output correlation is the same as that in the OR circuit in the case where A = B = "0" or A or B = "1", but is different from that in the OR circuit only in the case where A = B = "1", with V_{out} being "0". Accordingly, this function can be realized by adding a circuit with which V_{out} becomes "0" in the case where A = B = "1". The XOR function can be achieved by employing the transistors Tr6, Tr7, and Tr8 (a p-channel spin MOSFET) in a complementary manner together with the transistors Tr3, Tr4, and Tr5 (an n-channel spin MOSFET). The inverter formed with the transistors Tr6 and Tr7 has a threshold value V_{inv4} higher than $V_{dd}/2$. Accordingly, only in the case where A = B = "1", V_{in_n} becomes "0", and the transistor Tr8

is turned on (see Fig. 31).

The variation in the current driving capacity β_{p8} of the transistor Tr8 between parallel magnetization and antiparallel magnetization is wider than that in the case of the transistors Tr1 and Tr2, and β_{p8} is 0.5 (antiparallel magnetization) or 50 (parallel magnetization). In the case of parallel magnetization (β_{p8} = 50), a sufficiently high current (I_{d_high}) flows, but in the case of antiparallel magnetization (β_{p8} = 0.5), the value of the current (I_{d_low}) is very small. Figs. 32A and 32B and Figs. 33A and 33B show the operating point V_m in the case of the transistor Tr8 is in the paralell magnetization configuration (β_{p8} = 50) and the transistor Tr5 is in the antiparalell magnetization configuration (β_{n5} = 0.5). The sum of currents flowing through the transistors Tr1 and Tr8 is indicated by solid lines, and the sum of currents flowing through the transistors Tr2 and Tr5 is indicated by broken lines. Here, the current I_{d_low} is ignored.

The operation of this circuit is shown in Table 6.

[Table 6]

β_{n1}	β_{n2}	β_{n5}	β_{p8}	V_m A / B	0 / 0	0 / 1	1 / 1	V_{out} (in order of Vm)			function
1	10	0.5	0.5		"1"	"0"	"0"	"0"	"1"	"1"	OR
10	1	0.5	0.5		"1"	"1"	"0"	"0"	"0"	"1"	AND
1	10	50	0.5		"0"	"0"	"0"	"1"	"1"	"1"	all"1"
10	1	50	0.5		"0"	"1"	"0"	"1"	"0"	"1"	XNOR
1	10	0.5	50		V_O("1")	V_P("0")	V_T("1")	"0"	"1"	"0"	XOR
10	1	0.5	50		V_O("1")	V_R("1")	V_T("1")	"0"	"0"	"0"	all"0"

4-1) AND/OR/XNOR

When the transistor Tr8 is put into an antiparalell magnetization configuration (β_{p8} = 0.5) in

the circuit shown in Fig. 30, the current flowing through the transistor Tr8 can be ignored, and the transistor Tr8 can be regarded as open. Accordingly, this circuit can be made equivalent to the circuit shown in Fig. 24, and the AND/OR/XNOR functions can be achieved by changing the magnetization states of the transistors Tr1, Tr2, and Tr5 (or the current driving capacities β_{p1}, β_{n2}, and β_{n5}).

4-2) XOR (see Figs. 32A and 32B)

The transistor Tr8 is put into a paralell magnetization configuration (β_{p8} = 50). In the other parts, the transistor Tr1 is put into an antiparalell magnetization configuration (β_{p1} = 1), the transistor Tr2 is put into a paralell magnetization configuration (β_{n2} = 10), and the transistor Tr5 is put into an antiparalell magnetization configuration (β_{n5} = 0.5), as in the OR circuit. In the case where A = B = "0" or A or B = "1", the transistor Tr8 is open, and operates in the same manner as the OR circuit. In the case where A = B = "1", V_m is charged with the current I_{d_high} of the transistor Tr8, so as to be $V_m = V_T < V_{inv\_2}$. Accordingly, V_{out} becomes "0". Where the transistor Tr1 is put into a paralell magnetization configuration (β_{p1} = 10), the transistor Tr2 is put into an antiparalell magnetization configuration (β_{n2} = 1), the transistor Tr5 is put into an antiparalell magnetization configuration (β_{n5} = 0.5), and the transistor Tr8 is put into a paralell magnetization configuration (β_{p8} = 50), the output V_{out} becomes "0" for all the input patterns (see Figs. 33A and 33B).

5) AND/OR/XNOR/XOR/NAND/NOR

As in the case shown in Fig. 15, an inverter may be added to the output of the circuit shown in Fig. 24. However, it is possible to achieve the circuit by employing the circuit shown in Fig. 30. The transistor Tr5 in Fig. 30 functions only in the case where A = B = "0", and the operating point V_m is "0". The transistor

Tr8 functions only in the case where A = B = "1", and the operating point V_m is "1". Taking this fact into consideration, a NAND/NOR can be realized with the circuit shown in Fig. 30.

Figs. 33A and 33B and Figs. 34A and 34B show the operating points in the case where the transistors Tr5 and Tr8 are in a paralell magnetization configuration (β_{n5} = β_{p8} = 50) in the circuit shown in Fig. 30. The operations of the circuits are shown in Table 7.

[Table 7]

β_{n1}	β_{n2}	β_{n5}	β_{p8}	V_m A B	0 0	0 1	1 1	V_{out} (in order of Vm)			function
1	10	0.5	0.5		"1"	"0"	"0"	"0"	"1"	"1"	OR
10	1	0.5	0.5		"1"	"1"	"0"	"0"	"0"	"1"	AND
1	10	50	0.5		"0"	"0"	"0"	"1"	"1"	"1"	all"1"
10	1	50	0.5		"0"	"1"	"0"	"1"	"0"	"1"	XNOR
1	10	0.5	50		"1"	"0"	"1"	"0"	"1"	"0"	XOR
10	1	0.5	50		"1"	"1"	"1"	"0"	"0"	"0"	all"0"
1	10	50	50		V_T("0")	V_P("0")	V_U("1")	"1"	"1"	"0"	NAND
10	1	50	50		V_S("0")	V_R("1")	V_V("1")	"1"	"0"	"0"	NOR

5-1) AND/OR

When the transistor Tr5 is put into an antiparalell magnetization configuration (β_{n5} = 0.5) and the transistor Tr8 is put into an antiparalell magnetization configuration (β_{p8} = 0.5), the transistors Tr5 and Tr8 are both open. Accordingly, this circuit is equivalent to the circuit shown in Fig. 21.

5-2) XNOR

When the transistor Tr5 is put into a paralell magnetization configuration (β_{n5} = 50) and the transistor Tr8 is put into an antiparalell magnetization configuration (β_{p8} = 0.5), the transistor

Tr8 is open. Accordingly, this circuit is equivalent to the circuit shown in Fig. 24.

5-3) XOR

When the transistor Tr5 is put into an antiparalell magnetization configuration (β_{n5} = 0.5) and the transistor Tr8 is put into a paralell magnetization configuration (β_{p8} = 50), the circuit becomes an XOR equivalent to the circuit shown in Figs 32A and 32B.

5-4) NAND (see Figs. 34A and 34B)

The transistor Tr1 is put into an antiparalell magnetization configuration (β_{p1} = 1), the transistor Tr2 is put into a paralell magnetization configuration (β_{n2} = 10), the transistor Tr5 is put into a paralell magnetization configuration (β_{n5} = 50), and the transistor Tr8 is put into a paralell magnetization configuration (β_{p8} = 50). In the case where A = B = "0", discharging is performed by the transistor Tr5, and the operating point V_m becomes $V_T < V_{inv2}$. Accordingly, the output V_{out} becomes "1". In the case where A or B is "1", the operating point V_m becomes $V_P < V_{inv2}$, and accordingly, the output V_{out} becomes "1". In the case where A = B = "1", V_m is charged by the transistor Tr8, so as to be $V_m = V_U > V_{inv2}$. Accordingly, V_{out} becomes "0".

5-5) NOR (see Figs. 35A and 35B)

The transistor Tr1 is put into a paralell magnetization configuration (β_{p1} = 10), the transistor Tr2 is put into an antiparalell magnetization configuration (β_{n2} = 1), the transistor Tr5 is put into a paralell magnetization configuration (β_{n5} = 50), and the transistor Tr8 is put into a paralell magnetization configuration (β_{p8} = 50). In the case where A = B = "0", charging is performed by the transistor Tr5, and the operating point V_m becomes $V_S < V_{inv2}$. Accordingly, the output V_{out} becomes "1". In the case where A or B is "1", the operating point V_m becomes $V_R > V_{inv2}$, and

accordingly, the output V_{out} becomes "0". In the case where A = B = "1", V_m is charged by the transistor Tr8, so as to be $V_m = V_V > V_{inv2}$. Accordingly, V_{out} becomes "0".

In the circuit shown in Fig. 30, the number of MOSFETs is 10, and the number of capacitors is 2. As this circuit can be realized with a CMOS configuration, the circuit layout can be made very compact.

Fig. 36 shows a circuit in which CMOS inverters using spin MOSFETs are connected in two stages. Each of the first-stage inverter and the second-stage inverter has an input of a νMOS structure. In this circuit, the same weighting is set on inputs A and B. The inputs A and B are input to the second-stage inverter, and the output V_{m1} of the first stage is also input to the second-stage inverter. The capacitance weighting is the same between the inputs A and B in the second-stage inverter, but the capacitance weighting differs between the input A (or B) and the output V_{m1}. For example, with the input capacitance with V_{m1} being C_{m1}, the relationship of $3C_{m1} = C_A$ (= C_B) should be established. In this logic circuit, the magnetization states of Q1, Q2, and Q4 are changed to rewrite the logic functions. With the output V_{m1}, the logic functions of NOR and NAND can be realized. With the output V_{m2}, the logic functions of XNOR, XOR, AND, OR, all"1", and all"0" can be realized. Since the logic amplitude may not reach the "0" level or "1" level with the outputs V_{m1} and V_{m2}, depending on the logic function, it is preferable that a CMOS inverter or the like is added to each output to amplify the signal. In such a case, however, the logic function is inverted. Also, it is possible to employ a spin MOSFET for Q2.

Next, a logic circuit of a second CMOS configuration is described for reference, in conjunction with the accompanying drawings. In this logic circuit, a threshold value variable inverter is

employed as the output-stage inverter, so as to form a rewritable logic circuit. A logic threshold value V_{inv} is a binary value (V_{inv_high} or V_{inv_low}), and is supplied through an inverter that includes a conventional nMOS and a p-channel spin MOSFET. This inverter functions as an A-D converter that amplifies an analog voltage ("1/2" as described below) to a digital logic level ("0" or "1"), but also controls the threshold value. The output-stage A-D converter can be realized by employed the logic threshold value variable inverter, with the spin MOSFETs of the E/E, E/D, and CMOS inverters (shown in Fig. 6) having the νMOS structure for the inputs being replaced with conventional MOSFETs. In the following, other circuits are described for reference.

1) NAND/NOR

Fig. 37 illustrates an example structure of a NAND/NOR circuit. This circuit differs from the circuit illustrated in Fig. 48, in that the value of Vm is not varied by spin MOSFETs but the threshold value is varied when the threshold value is amplified to the logic level by the inverter. As shown in Fig. 38, the load curve (the characteristics of the νMOS structure) of the logic circuit shown in Fig. 37 is represented by a single line, and the operating points are indicated only by V_O, V_P, and V_Q. Here, the functions are changed by varying the operating point with the logic threshold value V_{inv} that is higher (V_{inv_high}) or lower (V_{inv_low}) than the operating point V_P when A or B is "1". The region between the values V_{inv_high} and V_{inv_low} is "1/2". Fig. 39 shows the truth table in this case, and Table 8 shows the details of the operation of the above circuit.

[Table 8]

V_{inv}	V_m A B	0 0	0 1	1 1	V_{out} (in order of Vm)			function
V_{inv_low}		V_O("0")	V_P("1/2")	V_Q("1")	"1"	"0"	"0"	NOR
V_{inv_high}		V_O("0")	V_P("1/2")	V_Q("1")	"1"	"1"	"0"	NAND

In the case where A = B = "0", the operating point V_m is $V_O < V_{inv\_low}, V_{inv\_high}$, and the output V_{out} becomes "1" with the inverter. In the case where A = B = "1", the operating point V_m is $V_Q < V_{inv\_low}, V_{inv\_high}$, and the output V_{out} becomes "0" with the inverter. Here, the outputs do not depend on the logic threshold value V_{inv} of the inverter. In the case where A or B is "1", the relationship $V_{inv\_low} < V_P < V_{inv\_high}$ is established. In this case, if the threshold value V_{inv} is equal to V_{inv_low}, the output V_{out} is "0", and accordingly, the circuit functions as a NOR circuit. If the threshold value V_{inv} is equal to V_{inv_high}, the output V_{out} is "1", and accordingly, the circuit functions as a NAND circuit.

2) NAND/NOR/XOR

Fig. 40 illustrates a NAND/NOR+XNOR circuit. Fig. 41 shows the operating points of the circuit. The principles of the operation of this circuit are the same as those shown in Figs. 51 through 54. In NOR, the circuit that has the output V_{out} = "1" (V_m = "0", accordingly) in the case where A = B = "1" is formed with the transistors Tr3, Tr4, and Tr5 (an n-channel spin MOSFET). The transistor Tr5 is either in a high driving force state ($\beta_{n5} = 10$) or in a low driving force state ($\beta_{n5} = 1$). The details of the operation are shown in Table 9.

[Table 9]

V_{inv}	β_{n5}	V_m A 0 0 1 B 0 1 1	V_{out} (in order of Vm)	function
V_{inv_low}	1	V_O("0") V_P("1/2") V_Q("1")	"1" "0" "0"	NOR
V_{inv_high}	1	V_O("0") V_P("1/2") V_Q("1")	"1" "1" "0"	NAND
V_{inv_low}	10	V_O("0") V_P("1/2") V_R("0")	"1" "0" "1"	XNOR
V_{inv_high}	10	V_O("0") V_P("1/2") V_R("0")	"1" "1" "1"	all"1"

2-1) NAND/NOR (see Figs. 42A and 42B)

In the circuit shown in Fig. 40, the transistor Tr5 is put into the state in which β_{n5} is "1", so that the drain current I_{id_low} can be ignored. Accordingly, the transistor Tr5 can be regarded as open, and the circuit becomes equivalent to the NAND/NOR circuit shown in Fig. 37.

2-2) XNOR (see Figs. 43A and 43B)

In Fig. 40, the transistor Tr5 is put into the state in which β_{n5} is 10, and the threshold value of the inverter is set at V_{inv_low} as in the NOR circuit. In the case where A = B = "0" or A or B = "1", the transistor Tr5 is regarded as open, and operates in the same manner as the NOR circuit. In the case where A = B = "1", V_m is charged with the current I_{d_high} of the transistor Tr5, so as to be $V_m = V_R < V_{inv\_low}$, and the output V_{out} becomes "1".

Further, when the transistor Tr5 is put into the state in which β_{n5} is 10 and the threshold value is set at V_{inv_high}, the output V_{out} becomes "1" for all inputs.

3) NAND/NOR/XNOR/XOR

Fig. 44 illustrates a NAND/NOR/XNOR/XOR circuit. In the XOR circuit, the input/output correlation is the same as that in the NAND circuit in the case where A = B = "1" or A or B = "1", but is different from that in the AND circuit only in the case where A = B = "0", with V_{out} being "0". Accordingly, this function can be realized by adding a circuit with which V_{out} becomes "0"

(with V_m being "1") in the case where A = B = "0". The XOR function can be achieved by employing the p-channel transistors Tr6, Tr7, and Tr8 (a p-channel spin MOSFET) in a complementary manner together with the n-channel transistors Tr3, Tr4, and Tr5 (an n-channel spin MOSFET). The transistor Tr8 is either in a high driving force state (β_{p8} = 10) or a low driving force state (β_{p8} = 1). The source follower of the transistors Tr6 and Tr7 is a positive level shifter, and the transistor Tr8 is turned on only in the case where A = B = "0".

Fig. 45 shows the operating characteristics of the transistors Tr6 and Tr7. According to the operating characteristics, V_{in_p} is determined. The operating point V_D in the case where A = B = "1" and the operating point V_E in the case where A or B is "1" are both higher than the threshold value of the transistor Tr8. Accordingly, no current flows, and the circuit can be regarded as open. Only with the operating point V_F in the case where A = B = "0", the transistor Tr8 is turned on. (If p-channel spin MOSFETs with threshold values higher than $V_{dd}/2$ can be integrated, the transistors Tr6 and Tr7 are unnecessary, and the V_{fg} node should be connected directly to the gate of the transistor Tr8.) In the case where β_{p8} is 10, a sufficiently high current I_{d_high} flows, but in the case where β_{p8} is 1, the value of the current (I_{d_low}) is very small. Figs. 46A and 46B show the operating points V_m in the case where β_{p8} is 10 and in the case where β_{n5} is 1. The sum of the currents flowing through the transistors Tr1 and Tr8 is indicated by solid lines, and the current I_{d_low} is ignored in Figs. 46A and 46B.

The details of the operation are shown in Table 10.

[Table 10]

V_{inv}	β_{n5}	β_{p8}	V_m			V_{out} (in order of Vm)			function
			A	0	0	1			
			B	0	1	1			
V_{inv_low}	1	1	"0"	"1/2"	"1"	"1"	"0"	"0"	NOR
V_{inv_high}	1	1	"0"	"1/2"	"1"	"1"	"1"	"0"	NAND
V_{inv_low}	10	1	"0"	"1/2"	"0"	"1"	"0"	"1"	XNOR
V_{inv_high}	10	1	"0"	"1/2"	"0"	"1"	"1"	"1"	all"1"
V_{inv_low}	1	10	V_O("1")	V_P("1/2")	V_Q("1")	"0"	"0"	"0"	all"0"
V_{inv_high}	1	10	V_O("1")	V_P("1/2")	V_Q("1")	"0"	"1"	"0"	XOR

3-1) NAND/NOR/XNOR

The transistor Tr8 is put into a non-driving force state (β_{p8} = 1), so that the current flowing through the transistor Tr8 can be ignored. Accordingly, this part can be regarded as open, and the circuit becomes equivalent to the circuit shown in Fig. 40. By simply changing β_{n5} and V_{inv}, the NAND/NOR/XOR functions can be maintained.

3-2) XOR

The transistor Tr8 is put into the state in which β_{p8} is 10, and the threshold value of the inverter is set at V_{inv_high} as in the NAND circuit. The transistor Tr5 is put into the state in which β_{n5} is 1, so as to be open. In the case where A = B = "1" or A or B = "1", the transistor Tr8 is open, and operates in the same manner as the NAND circuit. In the case where A = B = "0", V_m is charged by the p-channel spin MOSFET, so as to be $V_m = V_O < V_{inv\_high}$, and the output V_{out} becomes "0". Further, when the transistor Tr8 is put into the state in which β_{p8} is 10 and the threshold value is set at V_{inv_low}, the output V_{out} becomes "0" for all inputs.

4) NAND/NOR/XNOR/XOR/OR/AND

In the circuit shown in Fig. 44, the transistor Tr5 functions only in the case where A = B = "1", and V_m is "0". The transistor Tr8 functions only in the case where A = B = "0", and V_m is "1".

Taking this fact into consideration, an OR/AND can be realized with the circuit shown in Fig. 44. In the circuit, the number of MOSFETs is 10, and the number of capacitors is 2. Fig. 46A shows the load curve in the case where $\beta_{n5} = \beta_{p8} = 10$ in Fig. 44. Although the spin MOSFETs of two different types having different rates of change in driving force (the rate of change between Tr1 and Tr2 is 10, and the rate of change between Tr5 and Tr8 is 100, for example) need to be integrated in the circuit shown in Fig. 30, the circuit shown in Fig. 44 requires only one type of spin MOSFET.

The details of the operation are shown in Table 11.

[Table 11]

V_{inv}	β_{n5}	β_{p8}	V_m A / B	0 / 0	0 / 1	1 / 1	V_{out} (in order of Vm)			function
V_{inv_low}	1	1		"0"	"1/2"	"1"	"1"	"0"	"0"	NOR
V_{inv_high}	1	1		"0"	"1/2"	"1"	"1"	"1"	"0"	NAND
V_{inv_low}	10	1		"0"	"1/2"	"0"	"1"	"0"	"1"	XNOR
V_{inv_high}	10	1		"0"	"1/2"	"0"	"1"	"1"	"1"	all"1"
V_{inv_low}	1	10		"1"	"1/2"	"1"	"0"	"0"	"0"	all"0"
V_{inv_high}	1	10		"1"	"1/2"	"1"	"0"	"1"	"0"	XOR
V_{inv_low}	10	10		V_O("1")	V_P("1/2")	V_R("0")	"0"	"0"	"1"	AND
V_{inv_high}	10	10		V_O("1")	V_P("1/2")	V_R("0")	"0"	"1"	"1"	OR

4-1) NAND/NOR (see Figs. 46A and 46B)

With β_{n5} being 1 and β_{p8} being 1, the transistors Tr5 and Tr8 are both open. Accordingly, this circuit is equivalent to the circuit shown in Fig. 37, and functions as a NOR ciruict with V_{inv_low}, and as a NAND circuit with V_{inv_high}.

4-2) XNOR

With β_{n5} being 10 and β_{p8} being 1, the transistor

Tr8 is open with V_{inv_low},. Accordingly, this circuit is equivalent to the circuit shown in Fig. 43, and functions as a XNOR circuit.

4-3) XOR

With β_{n5} being 1 and β_{p8} being 10, this circuit is equivalent to the circuit shown in Fig. 43B, and functions as a XNOR circuit.

4-4) AND/OR

The value β_{n5} is set at 10, and the value β_{p8} is set at 10 in the circuit shown in Fig. 44 (see Figs. 47A and 47B). In the case where A = B = "0", charging is performed by the transistor Tr8, and the operating point $V = V_O > V_{inv\_low}, V_{inv\_high}$. Accordingly, the output V_{out} becomes "0". In the case where A = B = "1", discharging is performed by the transistor Tr5, and the operating point V_m becomes $V_Q < V_{inv?low}, V_{inv\_high}$. Accordingly, the output V_{out} becomes "1". In the case where A or B is "1", the transistors Tr5 and Tr8 are both open, and accordingly, the circuit becomes equivalent to the circuit shown in Fig. 37. Since the relationship $V_{inv\_low} < V_P < V_{inv\_high}$ is established, the circuit functions as an AND circuit, with V_{inv} being $V_{inv?low}$. The circuit functions as an OR circuit, with V_{inv} being V_{inv_high}.

The above circuit may be of either an n-channel type or a p-channel type, as long as the transistors Tr1 and Tr2 are of the same conductivity type in each circuit diagram.

In the following, a logic circuit in accordance with the above examples of reconfigurable circuits using spin MOSFETs is described in conjunction with the accompanying drawings. This logic circuit employs circuit groups including enhancement MOSFETs and n-channel spin MOSFETs.

1) NAND/NOR Circuit

Fig. 48 illustrates an example structure of a rewritable NAND/NOR circuit. As shown in Fig. 48, a

rewritable NAND/NOR circuit includes a logic gate stage and an inverter stage. The logic gate stage has a series-connection structure in which a νMOS (Tr1) and a spin MOSFET (Tr2) are connected in series. The νMOS (Tr1) has two inputs A and B, and the voltage V_{fg} to be applied to the floating gate according to the input value is determined by the equation: (A+B)/2, for example. The current gain of the νMOS (Tr1) is represented by β_{n1}. The inputs are represented by A and B, and the output is represented by V_{out}, which is either "0" (Low level, 0V) or "1" (High level, the source voltage V_{dd}). The above νMOS (Tr1) functions as a D-A converter that converts a digital input of "0" or "1" to a voltage of 0, $V_{dd}/2$, or V_{dd}.

Tr2 is a spin MOSFET (distinguished from a conventional MOSFET by the addition of an arrow), and a constant bias V_b is applied to Tr2. The driving force can be either β_{n2} = 1 or β_{n2} =10, depending on the magnetization state stored in the spin MOSFET (Tr2).

The static characteristics of the spin MOSFET (Tr2) are shown by the solid line in Fig. 49. The νMOS (Tr1) and the spin MOSFET (Tr2) function as a source follower circuit. The νMOS (Tr1) charges the V_m node, which is the connecting point between the νMOS (Tr1) and the spin MOSFET (Tr2), with the driving force according to V_{fg}. The spin MOSFET (Tr2) discharges the V_m node with the driving force according to the magnetization state. The νMOS (Tr1) and the spin MOSFET (Tr2) constitute the logic gate. Fig. 49 shows the load curve according to the νMOS (Tr1) (indicated by the broken line) and the operating points (V_O through V_S) of this logic gate.

The analog voltage V_m supplied at the operating points (V_O through V_S) is inverted and amplified to the digital logic level "0" or "1" by an inverter with the characteristics shown in the lower half of Fig. 49, with V_{inv} being the threshold value. The analog voltage

V_m is then output to an output terminal V_{out}.

Table 12 shows the relationship among β_{n2}, the operating points, and the circuit functions.

[Table 12]

β_{n2}	V_m A B	0 0	0 1	1 1	V_{out} (in order of Vm)			function
1		V_O("0")	V_S("1")	V_Q("1")	"1"	"0"	"0"	NOR
10		V_O("0")	V_R("0")	V_P("1")	"1"	"1"	"0"	NAND

The driving force of the spin MOSFET (Tr2) in a paralell magnetization configuration is $\beta_{n2} = 10$. In the case where A = B = "0", the drain current I_d is 0. The analog voltage V_m is $V_O < V_{inv}$, and the output V_{out} is "1", with the inverting amplification of the A-D converter being taken into consideration. In the case where A = B = "1", the drain current I_d is expressed as $I_d = \beta_{n1} (V_{dd} - V_m - V_{th})^2/2$. Here, V_m is $V_P > V_{inv}$, and V_{out} is "0". The above outputs do not depend on the driving force β_{n2} of the spin MOSFET (Tr2) (not depending on whether the magnetization state is parallel or antiparallel). In the case where A or B is "1", the drain current I_d is expressed as $I_d = \beta_{n1} (V_{dd}/2 - V_m - V_{th})^2$. Here, one of the inputs is "1", and V_m is discharged by Tr2. As a result, V_m becomes $V_R < V_{inv}$, and V_{out} is "1". Thus, the circuit functions as a NAND circuit.

The driving force of the spin MOSFET (Tr2) in an antiparalell magnetization configuration is $\beta_{n2} = 1$. In the case where A = B = "0", the analog voltage V_m is $V_O < V_{inv}$, and the output V_{out} is "1", with the inverting amplification of the A-D converter being taken into consideration. In the case where A = B = "1", V_m is $V_Q > V_{inv}$, and V_{out} is "0". The above outputs do not depend on the driving force β_{n2} of the spin MOSFET (Tr2) (not

depending on whether the magnetization state is parallel or antiparallel). In the case where A or B is "1", V_m is charged by Tr1. As a result, V_m becomes $V_S > V_{inv}$, and V_{out} is "0". Thus, the circuit functions as a NOR circuit. Fig. 50 shows the truth table of the circuit shown in Fig. 48.

As shown in Table 12, based on whether the driving force β_{n2}, which can vary according to the magnetization state in the spin MOSFET, is 1 or 10, a NOR logic or a NAND logic can be selected as the output V_{out} in response to the inputs A and B. Since the magnetization state of the spin MOSFET is stored in a non-volatile manner, a NOR logic or a NAND logic can be selected in a single circuit. If a circuit having such a function is formed with a conventional CMOS digital circuit, ten MOSFETs are necessary. The circuit of this example is advantageous in that the same function can be realized with only four MOSFETs.

2) NAND/NOR+XNOR

Referring now to Fig. 51A, a rewritable NAND/NOR+XNOR circuit is described. In an XNOR circuit, the input/output correlation is the same as that in an NOR circuit, in the case of A = B = "0" or A or B = "1". The input/output correlation is different from that in an NOR circuit only in the case where A = B = "1", with V_{out} being "1". Therefore, in the case where A = B = "1", V_{out} should be set to "1" (V_m being "0"). Here, a circuit that is formed with two conventional nMOSFETs (Tr3 and Tr4) and one n-channel spin MOSFET (Tr5) is added. The n-channel spin MOSFET (Tr5) can be switched between a high driving force state ($\beta_{n5} = 10$) and a low driving force state ($\beta_{n5} = 1$) in accordance with the magnetization state.

The source followers of Tr3 and Tr4 form a negative level shifter, and Tr5 is turned on only in the case where A = B = "1". In Fig. 51B illustrating the operation, the upper graph shows the operating

characteristics of Tr3 and Tr4 in Fig. 51A. According to the operating characteristics, V_{in_n} is determined. The static characteristics of Tr4 are indicated by the solid line, and the load curve of Tr3 is indicated by the broken lines. The operating point VC in the case where A = B = "0" and the operating point VD in the case where A or B is "1" are smaller than the threshold value of Tr5. Therefore, no current flows in Tr5, which can be regarded as open. Only the gate voltage of Tr5 at the operating point VE in the case where A = B = "1" is greater than the threshold. Accordingly, Tr5 is turned on. If n-channel spin MOSFETs with threshold values greater than $V_{dd}/2$ can be integrated, Tr3 and Tr4 are not necessary, and the V_{fg} node should be connected directly to the gate of Tr5. In the case where β_{n5} is 10, a sufficiently high current I_{d_high} flows, but in the case where β_{n5} is 1, the value of the current (I_{d_low}) is very small, as can be seen from the lower graph in Fig. 51B.

Figs. 52A through 54B show the operating points V_m with the respective values of β. The sum of the currents flowing through Tr2 and Tr5 is indicated by the solid lines, and the current I_{d_low} is ignored. Table 13 collectively shows the relationship between β_{n2}, β_{n5}, and the functions of the circuit.

[Table 13]

β_{n2}	β_{n5}	V_m A B	0 0	0 1	1 1	V_{out} (in order of Vm)			function
1	1		V_O("0")	V_S("1")	V_Q("1")	"1"	"0"	"0"	NOR
10	1		V_O("0")	V_R("0")	V_P("1")	"1"	"1"	"0"	NAND
1	10		V_O("0")	V_S("1")	V_U("0")	"1"	"0"	"1"	XNOR
10	10		V_O("0")	V_R("0")	V_V("0")	"1"	"1"	"1"	all"1"

Figs. 52A and 52B illustrate the NAND/NOR

functions. Tr5 is put into a non-driving force state (β_{n5} = 1), so that the current flowing through Tr5 can be ignored. Accordingly, the part of Tr5 (Fig. 51A) can be regarded as open. Thus, the NAND/NOR functions can be maintained.

Figs. 53A and 53B illustrate the XNOR function. Tr5 is put into a high driving force state (β_{n5} = 10), and Tr2 is put into the state in which β_{n2} = 1. In the case where A = B = "0" or A or B = "1", Tr5 is regarded as open, and operates in the same manner as the NOR circuit. In the case where A = B = "1", V_m is discharged with the current V_{inv_high} of Tr5, so as to be $V_m = V_U < V_{inv}$, and the output V_{out} becomes "1". Further, when Tr5 is put into the state in which β_{n5} is 10 and Tr2 is put into the state in which β_{n2} is 10, the output V_{out} becomes "1" for all inputs (all "1"), as shown in Figs. 54A and 54B.

3) NAND/NOR/XNOR+AND/OR/XOR Functions

Another stage of inverter is added to the output terminal V_{out} shown in Fig. 51A, so that V_{out} is inverted. As shown in Fig. 55, NAND/NOR/XNOR becomes AND/OR/XOR. With the two outputs of V_{out} and the inverted V_{out}, a circuit that can achieve all the symmetric Boolean functions of NAND/NOR/XNOR + AND/OR/XOR, all"0", and "1" can be formed. In the entire circuit, nine MOSFETs and two capacitances are required. If necessary, a circuit (a pass transistor) for selecting either V_{out} or the inverted V_{out} is added to the output terminal, thereby restricting the number of outputs to 1. Table 14 collectively shows the functions of the circuit illustrated in Fig. 55.

[Table 14]

β_{n2}	β_{n5}	V_{out} A B	0 0	0 1	1 1	$\overline{V_{out}}$ A B	0 0	0 1	1 1	function
1	1		"1"	"0"	"0"		"0"	"1"	"1"	NOR/OR
10	1		"1"	"1"	"0"		"0"	"0"	"1"	NAND/AND
1	10		"1"	"0"	"1"		"0"	"1"	"0"	XNOR/XOR
10	10		"1"	"1"	"1"		"0"	"0"	"0"	all"1"/all"0"

As described so far, any of the logic circuits in accordance with the embodiments of the present invention includes a spin transistor or a spin MOSFET that can change the current driving force in a non-volatile manner, and a νMOS structure. In such a structure, symmetric Boolean functions that are reconfigurable in a non-volatile manner can be realized with a small number of devices. With this circuit, the chip area can be reduced, and high-speed, low-consumption electric operations can be expected. Accordingly, this circuit can be applied to the integrated circuits for mobile devices that are produced in a short time.

Although the logic circuits in accordance with the specific examples and embodiments of the present invention have been described so far, the present invention is not limited to them. It should be obvious to those skilled in the art that various changes and modifications can be made to the above examples and embodiments, and various combinations of them can also be made.

INDUSTRIAL APPLICABILITY

Using a logic circuit of the present invention, symmetric Boolean functions that are reconfigurable in a non-volatile manner can be realized with a smaller number of devices. Since a circuit of the present invention can maintain each logic function in a non-

volatile manner, there is no need to employ a non-volatile memory for storing logic functions. Accordingly, the chip size can be reduced. Also, using a circuit with a smaller number of devices, high-speed, low-consumption electric operations can be expected. Thus, the circuits of the present invention can be applied to the integrated circuits for mobile devices that are produced in a short time.

CLAIMS

1. A circuit comprising

a spin transistor having transfer characteristics depending on the spin direction of conduction carriers,

the spin direction of the conduction carriers being changed so as to vary the transfer characteristics of the spin transistor,

an operating point being changed based on the transfer characteristics, thereby reconfiguring a function.

2. A circuit comprising

a spin transistor that includes at least two ferromagnetic layers, and has transfer characteristics depending on the magnetization state of the ferromagnetic layers,

the magnetization state of the spin transistor being changed to move an operating point, thereby reconfiguring a function.

3. The circuit as claimed in claim 2, wherein:

the spin transistor has at least one ferromagnetic body ("free layer") with a magnetization direction that can be controlled independently, and at least one ferromagnetic body ("pin layer") with a fixed magnetization direction; and

the circuit reconfigures a function by changing an operating point based on two magnetization states including a first state in which the free layer and the pin layer have the same magnetization directions ("parallel magnetization"), and a second state in which the free layer and the pin layer have the opposite magnetizing states to each other ("antiparallel magnetization").

4. The circuit as claimed in any of claims 1

to 3, further comprising:

a first terminal that generates the operating point and serves as an output;

a first circuit group for charging the first terminal; and

a second circuit group for discharging the first terminal,

wherein the spin transistor is included in one or both of the first circuit group and the second circuit group.

5. The circuit as claimed in claim 4, wherein the first terminal has a potential that is determined by changing the spin directions of the carriers of the spin transistor or by controlling the transfer characteristics depending on the magnetization state of the spin transistor.

6. The circuit as claimed in any of claims 1 to 5, which outputs a signal based on a signal that is input via a neuron MOS (νMOS) structure including a plurality of inputs weighted with capacitances by capacitors and a floating gate connecting the inputs.

7. The circuit as claimed in claim 6, wherein the input signals are weighted so as to be substantially equal to one another.

8. The circuit as claimed in any of claims 4 to 7, wherein a logic threshold value for dividing the potential generated in the first terminal into an output of a logic level "0" and an output of a logic level "1" is set with respect to the operating point that varies according to a variation in the transfer characteristics of the spin transistor.

9. The circuit as claimed in any of claims 1

to 8, wherein an A-D converter with a predetermined logic threshold value is connected to an output terminal of the circuit.

10. The circuit as claimed in any of claims 1 to 9, wherein the spin transistor is a MOSFET-type spin transistor ("spin MOSFET") that are formed with a source and a drain, including a MOS structure and a ferromagnetic body.

11. The circuit as claimed in any of claims 3 to 9, wherein the first circuit group includes a MOSFET of a first conductivity type or a spin MOSFET of the first conductivity type, and the second circuit group includes a MOSFET of the same conductivity type as the first conductivity type or a spin MOSFET of the same conductivity type as the first conductivity type.

12. The circuit as claimed in any of claims 3 to 11, comprising

an E/E circuit that includes a structure in which the source of an enhancement MOSFET or an enhancement spin MOSFET contained in the first circuit group is connected to the drain of an enhancement MOSFET or an enhancement spin MOSFET contained in the second circuit group, and a first terminal that is formed at the connection portion.

13. The circuit as claimed in claim 12, wherein the drain of an enhancement MOSFET or an enhancement spin MOSFET contained in the first circuit group in the E/E circuit is connected to the gate of the enhancement MOSFET or the enhancement spin MOSFET.

14. The circuit as claimed in claim 12 or 13, wherein an enhancement MOSFET or an enhancement spin MOSFET contained in the second circuit group in the E/E

circuit has a νMOS structure.

15. The circuit as claimed in any of claims 3 to 11, comprising

an E/D circuit that includes a structure in which the source of a depletion MOSFET or a depletion spin MOSFET contained in the first circuit group is connected to the drain of an enhancement MOSFET or an enhancement spin MOSFET contained in the second circuit group, and a first terminal that is formed at the connection portion.

16. The circuit as claimed in claim 15, wherein the source of a depletion MOSFET or a depletion spin MOSFET contained in the first circuit group in the E/D circuit is connected to the gate of the depletion MOSFET or the depletion spin MOSFET.

17. The circuit as claimed in claim 15 or 16, wherein an enhancement MOSFET or an enhancement spin MOSFET contained in the second circuit group in the E/D circuit has a νMOS structure.

18. The circuit as claimed in any of claims 11 to 17, wherein the νMOS structure has two inputs (A and B) weighted with capacitances by capacitors.

19. The circuit as claimed in any of claims 4 to 18, wherein the circuit is a NAND/NOR reconfigurable logic circuit or an AND/OR reconfigurable logic circuit that includes the A-D converter having the first terminal as an input.

20. The circuit as claimed in any of claims 11 to 19, wherein the first and second circuit groups or one of the first and second circuit groups comprises

a circuit that controls the potential of the

first terminal by connecting the source or the drain of another spin MOSFET to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET, the level shift circuit turning on the another spin MOSFET only when a predetermined input is made.

21. The circuit as claimed in any of claims 11 to 20, wherein the second circuit group comprises a circuit that controls the potential of the first terminal by connecting the drain of another spin MOSFET of n-channel type to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET of n-channel type, the another spin MOSFET of n-channel having the source grounded, the level shift circuit turning on the another spin MOSFET of n-channel type only when an input is A = B = "0".

22. The circuit as claimed in any of claims 11 to 21, wherein the first circuit group comprises a circuit that controls the potential of the first terminal by connecting the drain of another spin MOSFET of p-channel type to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET of p-channel type, the another spin MOSFET of p-channel having the source connected to a supply voltage, the level shift circuit turning on the another spin MOSFET of p-channel type only when an input is A = B = "1".

23. The circuit as claimed in any of claims 20 to 23, wherein the level shift circuit is formed with an E/E, E/D, or CMOS inverter.

24. The circuit as claimed in any of claims 20 to 23, wherein the circuit is a reconfigurable logic circuit that includes the A-D converter having the

first terminal as an input.

25. The circuit as claimed in claim 20 or 24, wherein the circuit is a reconfigurable logic circuit that includes an inverter having the output of the A-D converter as an input, and can achieve all symmetric Boolean functions.

26. The circuit as claimed in any of claims 3 to 9, wherein the first circuit group includes a MOSFET of a first conductivity type or a spin MOSFET of the first conductivity type, and the second circuit group includes a MOSFET of a second conductivity type different from the first conductivity type or a spin MOSFET of the second conductivity type.

27. The circuit as claimed in claim 26, comprising

a CMOS circuit that includes a structure in which a p-channel MOSFET or a p-channel spin MOSFET contained in the first circuit group is connected to an n-channel MOSFET or an n-channel spin MOSFET contained in the second circuit group with a shared drain terminal, and a first terminal that is formed at the shared drain terminal.

28. The circuit as claimed in claim 26, comprising

a CMOS circuit that is formed with a p-channel spin MOSFET contained in the first circuit group and an n-channel spin MOSFET contained in the second circuit group.

29. The circuit as claimed in any of claims 26 to 28, wherein the p-channel MOSFET or the p-channel spin MOSFET, and the n-channel MOSFET or the n-channel spin MOSFET of the CMOS circuit have a shared floating

gate forming a νMOS structure.

30. The circuit as claimed in claim 29, wherein the νMOS structure has two inputs (A and B) weighted with capacitances by capacitors.

31. The circuit as claimed in any of claims 26 to 30, wherein the circuit is an AND/OR reconfigurable logic circuit or a NAND/NOR reconfigurable logic circuit that includes an A-D converter having the first terminal as an input.

32. The circuit as claimed in any of claims 26 to 31, wherein the first and second circuit groups, or one of the first and second circuit groups comprises

a circuit that controls the potential of the first terminal by connecting the source or the drain of another spin MOSFET to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET, the level shift circuit turning on the another spin MOSFET only when a predetermined input is made.

33. The circuit as claimed in any of claims 26 to 32, wherein the second circuit group comprises

a circuit that controls the potential of the first terminal by connecting the drain of another spin MOSFET of n-channel type to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET of n-channel type, the another spin MOSFET of n-channel having the source grounded, the level shift circuit turning on the another spin MOSFET of n-channel type only when an input is A = B = "0".

34. The circuit as claimed in any of claims 26 to 33, wherein the circuit is an AND/OR/XNOR reconfigurable logic circuit or a NAND/NOR/XOR

reconfigurable logic circuit that includes an A-D converter having the first terminal as an input.

35. The circuit as claimed in any of claims 26 to 35, wherein the first circuit group comprises

a circuit that controls the potential of the first terminal by connecting the drain of the another spin MOSFET of p-channel type to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET of p-channel type, the another spin MOSFET of p-channel having the source connected to a supply voltage, the level shift circuit turning on the another spin MOSFET of p-channel type only when an input is A = B = "1".

36. The circuit as claimed in any of claims 26 to 35, wherein the circuit is an AND/OR/XOR reconfigurable logic circuit or a NAND/NOR/XNOR reconfigurable logic circuit that includes an A-D converter having the first terminal as an input.

37. The circuit as claimed in any of claims 26 to 36, wherein the circuit is a reconfigurable logic circuit that includes an inverter having the output of the A-D converter as an input, and can achieve all symmetric Boolean functions.

38. The circuit as claimed in claim 26 or 32, wherein the circuit is formed with a circuit group that is characterized by:

controlling the potential of the first terminal by connecting the drain of another spin MOSFET of n-channel type to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET of n-channel type, the another spin MOSFET of n-channel having the source grounded, the level shift circuit turning on the another spin MOSFET of n-channel

type only when an input is A = B = "1"; and

controlling the potential of the first terminal by connecting the drain of another spin MOSFET of p-channel type to the first terminal, and connecting a level shift circuit to the gate of the another spin MOSFET of p-channel type, the another spin MOSFET of p-channel having the source connected to a supply voltage, the level shift circuit turning on the another spin MOSFET of p-channel type only when an input is A = B = "0".

39. The circuit as claimed in claim 38, wherein the circuit is an all symmetric Boolean function logic circuit that includes an A-D converter having the first terminal as an input.

40. The circuit as claimed in any of claims 32 to 39, wherein the level shift circuit is formed with an E/E, E/D, or CMOS inverter.

41. An A-D converter comprising

a CMOS inverter,

one of a p-channel MOSFET or an n-channel MOSFET of the CMOS inverter being a spin MOSFET, or a p-channel MOSFET and an n-channel MOSFET of the CMOS inverter being spin MOSFETs.

42. The A-D converter as claimed in claim 41, wherein a logic threshold value can be changed according to the magnetization state of the spin MOSFET.

43. A logic circuit comprising

an A-D converter that has a variable logic threshold value and is connected to an output stage of a circuit having an analog output, the logic circuit being capable of reconfiguring a logic function.

44. A circuit comprising

a transistor with variable transfer characteristics,

the circuit being capable of reconfiguring a function by moving an operating point through a change in the transfer characteristics of the transistor.

45. An integrated circuit comprising

the circuit as claimed in any of claims 1 to 44.